A Broadband Waveguide-to-Microstrip Transition for Millimeter-Wave applications

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Abstract**—**A novel waveguide-to-microstrip transition at millimeter wave frequencies is presented in this letter. An E-plane probe is chosen to couple the energy of the waveguides to the energy of microstrip lines or vice versa. Then, a stepped impedance microstrip line is placed following the probe to match the impedance between the probe and a 50 ohm microstrip line. This compact matching network widen the bandwidth of waveguide-to-microstrip transition. The proposed transition of full W-band is designed and optimized based on the results from numerical simulations. For the purpose of verification, the probe transitions connected in the form of back to back structure are measured. The measured results indicate that the insertion loss of the single transition is smaller than 11dB , and the return loss is better than 11dB over the frequency from 75GHz to 105GHz. It shows that the proposed transition have the advantages of low insertion loss, good return loss, and wide bandwidth. Its performance is suitable for millimeter wave applications.

Keywords—waveguide-to-microstrip transition, W-band, low insertion loss.

I. INTRODUCTION

Applications such as atmospheric monitoring, radio astronomy and imaging drive the development of compact and cheaper active systems and subsystems, which are usually built on planar circuits. However, some passive elements using waveguide technology with low-loss, high-Q still are required to obtain satisfied performances. Therefore, in order to take advantage of both planar and waveguide technologies, broad band low-loss waveguide to microstrip transitions are indispensable to combine integrated circuits with waveguide elements especially in the millimeter wave applications.

Different techniques have been explored for waveguide to microstrip transitions [1]-[9].Transition based on a fin-line taper in[1]exhibits good performance. The one with ridge waveguide is elaborately fabricated in[2].Besides above two designs, the probe transitions which are commonly selected because of lower transition loss, better return loss and broader band, are particularly suitable for millimeter-wave applications. Unlike in-line designs, the probe transition is achieved by an extension of the printed microstrip line through a small aperture on the middle of the broad wall of a waveguide. More waveguide to microstrip transitions have been proposed for decades[10]-[13].

The transition which has an extended microstrip line as an E-plane probe for transforming the energy in waveguides to microstrip lines is presented in this letter. A stepped impedance line which acts like matching network to compensate the reactance of the microstrip probe, and match the resulting impedance to a standard 50ohm microstrip line through an additional metallic buffer follows this E-plane probe. A aperture is created on the middle of the broad wall of a waveguide to ensure only

TE_{10} mode of the waveguide modes propagating along the direction towards the probe. To make the proposed transition suitable for easy attaching to test instrument, a curved bend waveguide is implemented for input and output. For verifying the simulation results, two proposed transitions in back-to-back connection are prepared to measure. The results indicate that the proposed transition in this letter exhibits low insertion loss and good return loss across the entire W-band.

II. DESIGN PROCEDURE

In this proposed design, we complete the transition between waveguide and a microstrip line in two steps, a beginning transformation between waveguide and a probe and following transformations between the probe and a microstrip line. Figure.1 shows the 3-D structure of the proposed waveguide-to-microstrip transition. It consists of three metallic pieces and a planar transmission line. A E-plane probe, a followed stepped impedance line and a 50ohm microstrip line constitute the planar transition line. The stepped impedance line serves as matching network, and is sandwiched in the middle of the metallic buffer to form a transition between waveguide and a microstrip line. Herein, a aperture must be created at the broad sidewall of the waveguide for extending a E-plane probe from the microstrip line. The dimensions of the aperture are properly selected to ensure only TE_{10} mode propagating along the direction towards the probe. The probe line, a stepped impedance line and a microstrip line, are fabricated on a 0.127mm thick Rogers RT/Duroid 5880 substrate with a dielectric constant of 2.2.

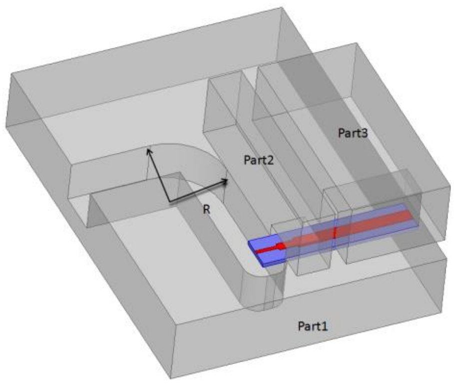

Figure 1. 3-D structure of the proposed waveguide to microstrip transition

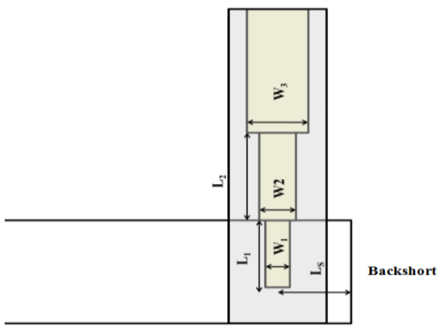

Figure 2. The top view of configuration the transition.

The top view of the transition is showed in Figure.2.Then,three parts of the design are discussed. A E-plane probe, which is utilized to couple the energy of TE_{10} mode in waveguides to the energy of quasi-TEM mode of microstrip lines or vice versa, is achieved by an extension of the printed microstrip line through a small aperture on the middle of the broad wall of a waveguide which is short-circuited. A matching network between the probe and the microstrip line is achieved by a stepped impedance line. Then, a metallic buffer is employed to provide a smooth transformation between the probe and a standard microstrip line. For the ease of machining and measuring, a bend of the waveguide is introduced.

The exact fields of a microstrip line constitute a hybrid TM-TE wave and require more advanced analysis techniques than we are prepared to deal with here. In most practical applications, however, the dielectric substrate is electrically very thin (d << λ) , and so the fields are quasi-TEM. In other words, the fields are essentially the same as those of the static (DC) case [18].

For a given characteristic impedance Z_0 and dielectric constant ε_r , the W / d ratio can be found as :

$$\frac{W}{d} = \begin{cases} \dfrac{8e^{A}}{e^{2A}-2} & for\, W/d < 2 \\ \dfrac{2}{p}\left[B-1-\ln(2B-1)+\dfrac{\varepsilon_r-1}{2\varepsilon_r}\left\{\ln(B-1)+0.39-\dfrac{0.61}{\varepsilon_r}\right\}\right] & for\, W/d > 2 \end{cases} \tag{1}$$

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r+1}{2}}+\frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23+\frac{0.11}{\varepsilon_r}\right)$$
$$B = \frac{377p}{2Z_0\sqrt{\varepsilon_r}} \tag{2}$$

Where, W is the width of microstrip, d is the thickness of substrate. In this design d=0.127mm， Z0=50 W，from above equations, we can know the proposed microstrip width of 0.39 mm. In this design, all the sizes of the microstrips are obtained from the theories mentioned above. All the required simulations are conducted by using the 3-D EM simulator—Ansoft's HFSS. Table I lists the values of the structural parameters for the proposed W-band transition. More details on each part of design are provided in the following subsections.

TABLE I. VALUES OF THE STRUCTURAL PARAMETERS FOR THE TRANSITION

Variable	L_S	L1	L2	W1	W2	W3	R	T1	H1	T2	H2	-
Value(mm)	1.0	0.67	0.55	0.10	0.25	0.39	1.6	1.0	0.3	1.27	1.05	-

A. Waveguide-to-microstrip probe

A extending microstrip entering a WR-10 (2.54mm x 1.27mm) waveguide as an E-plane probe is showed in Figure.3.For transferring maximum power between the waveguide and the probe, a waveguide backshort is placed behind the probe. The rigorous and thrifty analysis of the microstrip probe is very less published. In work [14], simplified sinusoidal current distribution on the probe is utilized for the spectral domain calculation of the input impedance. Based on finite element method, a more rigorous approach was demonstrated in[14].Instead of complicated formulations, the input impedance of the E-plane probe is determined by the probe length In this design,, probe width ,and backshort distance, the theory mentioned in[16][17]is used for setting the initial values, the input impedance of the probe is:

$$Z_{in} = R + jX_{10} \tag{3}$$

$$R = \frac{2h}{kabb_{10}} \tan^2(\frac{kL_1}{2}) \sin^2(b_{10}Ls) \tag{4}$$

$$X_{10} = \frac{\eta}{kab\beta_{10}} \tan^2(\frac{kL_1}{2}) \sin^2(2\beta_{10}Ls) \tag{5}$$

Herein, $k = 2p/l_0 = 2pf_0/c$, $\beta_{10} = \sqrt{k^2 - (\frac{\pi}{a})^2}$, $\eta = \sqrt{\frac{\mu}{\varepsilon}}$ .Here, μ and ε are the permeability and permittivity respectively. Ls is the distance from microstrip to the backshort of waveguide, and L_1 is the probe length. For the sizes of WR10 : a=2.54mm,b=1.27mm, f0=92.5GHz.When $2b_{10}Ls = kp$, $X_{10} = 0$, $Ls = \frac{p}{2b_{10}}$ » 1.016 mm, At this circumstance, $R = \frac{2h}{kabb_{10}} \tan^2(\frac{kL_1}{2})$,here in R=75 Ω , $\tan^2(\frac{kh}{2})$ » 1 , mm, the initial probe width is stetted 0.10mm.A parametric optimum is conducted to search an combination of these parameters to achieve the broadband performance of this transformation. The frequency responses of the proposed waveguide-to-microstrip transition are showed in Figure.4. The simulation results indicate that the insertion loss of the waveguide-to-microstrip line transformation is less than 0.15 dB and the return loss is more than 25 dB throughout the entire W-band.

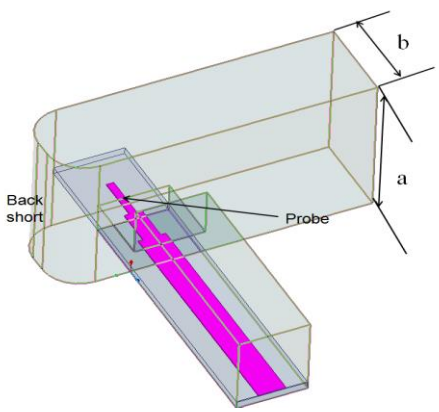

Figure 3. The view of waveguide to microstrip probe

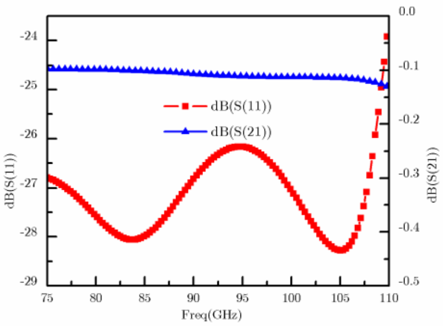

Figure 4. Simulation results of the waveguide-to-microstrip line

B. stepped impedance line in the middle of the metallic buffer

After obtaining the optimized probe structure, additional matching circuit elements should be designed to realize the impedance match between the microstrip probe and the standard 50 ohm microstrip line. A stepped impedance line is placed following the probe, it acts as a matching network to compensate the reactance of the microstrip probe, meanwhile it is placed in the middle of the metallic buffer for the transformation. A quarter wavelength transformer is usually used to match the resulting real impedance to the 50 ohm microstrip line [11]-[13]. According to impedance match theory, one drawback of the quarter wavelength transformer is its narrow bandwidth which could be improved by stepped matching transformers [18]. In this paper, for achieving maximum translation efficiency in the broad band, the situation is improved by applying a stepped impedance line.Figure.5 shows different views of the metallic buffer. The dimensions of the aperture on the middle of the broad wall must be as small as possible to avoid the perturbation of field distribution in the waveguide. For simplicity, the width of the aperture is fixed at 1mm as in [9], the dimension of the inner height H1follows the mechanical design for the stepped impedance line. The height H1ofthe metallic buffer influences the transformation of other modes in the waveguide to the microstrip except TE_{10} mode. Figure.6 plots the frequency responses of the transition versus the variations of H1without the probe and microstrip lines. It can be seen that the insertion loss decreases when H1 increases from 0.2mm to 0.6mm.While the height H1 also affects the matching from the high impedance. For considerations of machining and the influence of the height H1, the selected value of H1 is 0.3mm. The increase in the inner height H2of the metallic buffer helps to establish the electromagnetic field distributions of a standard microstrip line, by using the similar method, the value of H2 is 1.27mm.

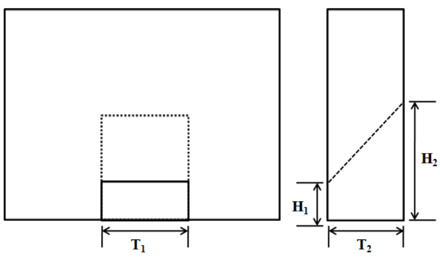

Figure 5. Front and side views of the metallic buffer for a transformation.

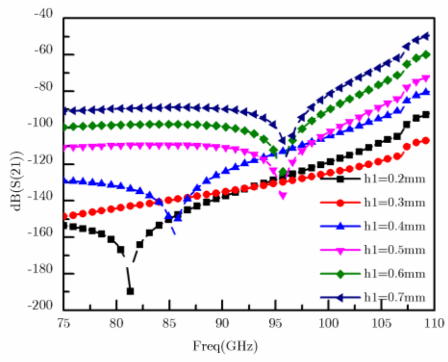

Figure 6. The insertion loss of the transition versus the variations of H1 without the probe and microstrip lines

C. The 90^{o} Curved Bend of waveguide

For the ease of fabricating and measuring the probe transition, a curved bend of waveguide is presented. The discontinuity of waveguide is introduced by the curved bend of waveguide, it will increase the insertion loss of the waveguide to microstrip transition. The loss is determined by the radius of the curved bend. A parametric study is conducted to search for an optimum combination of the parameter R to achieve the broadband performance.Figure.7 shows the return loss of the curved bend of waveguide versus the variations of R. When R increases from 1.2mm to 1.8mm, the result of simulation indicates that the optimized value of the radius R is 1.4mm.

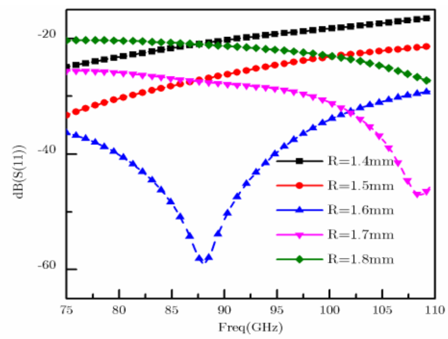

Figure 7. The return loss of the curved bend of waveguide versus the variations of R

Connecting with the curved bend waveguide, the frequency responses of a single transition between a waveguide to a standard microstrip line are also displayed in Figure.8.Comparing to another designs, the complete transition widens bandwidth, and still maintains good return loss, but suffers more insertion loss because of additional radiation loss and discontinuity. The 1-dB bandwidth ranges from 60 to117 GHz. And the metallic buffer (Part III) can be integrated with Part II into one piece for ease of fabrication and assembly. For the ease of fabricating and measuring the probe transition, a curved bend of waveguide is presented. The discontinuity of waveguide is introduced by the curved bend of waveguide, it will increase the insertion loss of the waveguide to microstrip transition. The loss is determined by the radius of the curved bend. A parametric study is conducted to search for an optimum combination of the parameter R to achieve the broadband performance. Figure.7 shows the return loss of the curved bend of waveguide versus the variations of R. When R increases from 1.2mm to 1.8mm, the result of simulation indicates that the optimized value of the radius R is 1.4mm.

Connected with the curved bend waveguide, the frequency responses of a single transition between a waveguide and a standard microstrip line are also displayed in Figure.8.Compared with other design, the complete transition widens bandwidth, and still maintains good return loss. However it suffers more insertion loss because of additional radiation loss and discontinuity. The 1-dB bandwidth ranges from 62 to 117 GHz. The metallic buffer (Part III) can be integrated with Part II into one piece for ease of fabrication and assembly.

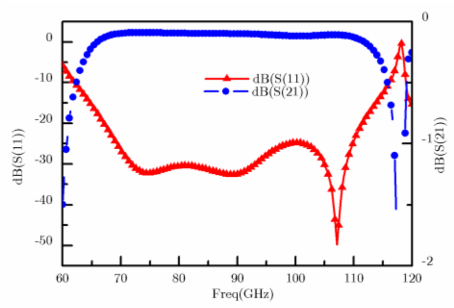

Figure 8. The frequency responses of a single transition

III. MEASUREMENTS

The proposed W-band waveguide-to-microstrip transition is fabricated and assembled in a waveguide test cavity. To facilitate the experimental verification of the simulation results, the proposed transitions in back-to-back connection with a 10mm microstrip line are prepared for measurements. Figure.9 shows the photo of the waveguide-to-microstrip transition in back-to-back connection. The Agilent network analyzer 8510C combined with two external mixers is employed to measure the proposed transitions. Figure.10 shows the measured results. The measured of insertion loss is less than 2 dB from 75GHz to 105GHz.The additional insertion loss of the measured data can be attributed to the problems caused by the fabrication and assembly errors. The test curve of insertion loss still agrees well with the simulation curve of insertion loss. Over the frequency range from 75 GHz to 105GHz, the return loss is better than 11dB.The return loss is not as good as the simulation result, which is limited by the test dynamic range of the millimeter wave scalar network analyzer. But the low insertion loss of the probe transition indicates its good performance. This transition has been used to design the LNA (low noise amplifier) module, also high gain and good noise figure are obtained.

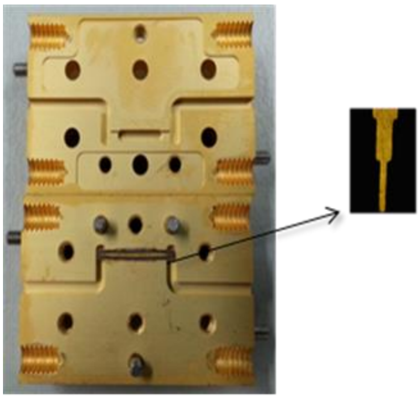

Figure 9. Photo of the waveguide-to-microstrip transition in back-to-back connection

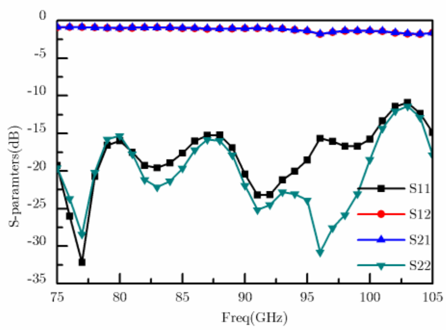

Figure 10. Measured results of the back to back transition structure

For rigorous verification of the well matched transition, we did further experiences. The experiments include two different back-to-back configurations with two different-length microstrips. The lengths of microstrips in two back-to-back configurations are $\lambda/4+L_{fix}$ and $\lambda/2+L_{fix}$, respectively. The waveguide-to-microstrip transition with different length of microstrips are fabricated and assembled in a similar waveguide cavity. Figure 11 shows the measured results of the back to back transition structure with three different length of microstrip line (L_{fix}, $\lambda/4+L_{fix}$, $\lambda/2+L_{fix}$).The measured of insertion loss is less than 2 dB from 75GHz to 105GHz in all different length. The additional insertion loss of the measured data can be also attributed to the problems caused by the fabrication and assembly errors. The return loss is better than 11dB over the frequency range from 75 GHz to 105GHz, and is not about the length of microstrip line. These results certify that the proposed transition is well matched to the microstrip line.

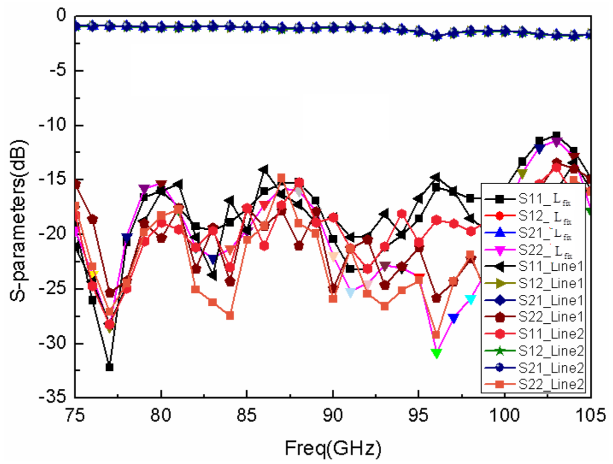

Figure 11. Measured results of the back to back transition structure with different length of microstrip line

Table. Ⅱ shows the performance comparisons of the fabricated transition in this work with others in literatures. It indicates that the transition of this paper has wider bandwidth and lower insertion loss at W-band, and it is suitable for the millimeter-wave applications.

TABLE II. Comparison with the reported transition

Ref.	Bandwidth (GHz)	Insertion loss(dB)	Return loss(dB)	Minimum insertion loss(dB)
[10]	85-120	0.8-2.0	≥10	0.8@85GHz
[11]	75-90	1.5-2.4	≥11.5	1.5@86GHz
[12]	50-72	0.5-0.9	≥11	0.5@70GHz
[13]	85-110	1.0-2.0	≥8	1.0@92 GHz
This work	75-105	0.9-1.7	≥11	0.9@75-84GHz

IV. CONCLUSIONS

The details of the design and fabrication of low loss waveguide to microstrip probe transition are presented in this letter. The proposed E-plane probe which is extending in the waveguide to couple energy of the waveguide to the microstrip line, has the advantage of ease in fabrication and assembly. A stepped impedance line follows the probe to implement impedance matching and widens the practical bandwidth, and a metallic buffer is introduced between the probe and the standard microstrip line to suppress the unwanted waveguide modes. Numerical simulations are conducted for the W-band waveguide to microstrip transitions. The measured results of the two proposed transitions in back-to-back connection indicate that the insertion loss is 0.9 to 1.7dB, and the return loss is better than 11dB over the frequency from 75GHz to 105GHz. It exhibits low insertion loss, good return loss and stable performance, which are verified experimentally. These features qualify the proposed transition for many millimeter-wave applications.

ACKNOWLEDGEMENT

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REFERENCES

[1] S.I. Shams, Q.C. Montreal, et al, “Ridge gap waveguide to microstrip line transition with perforated substrate,” Radio Science Meeting, 2014, pp. 215-218.doi:10.1109/USNC-URSI.2014.6955597.

[2] Shufeng Sun and Yi Huang, “A double waveguide frequency bands waveguide-to-microstrip transition,”3rd Asia-Pacific Conference on Antennas and Propagation, 2014, pp. 1172-1175. doi:10.1109/APCAP.2014.6992722.

[3] R. Hosono, Y Uemichi, Han Xu, et al, “A broadband waveguide to microstrip-line transition on multi-layered LCP substrate,” IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, 2015, pp. 1400-1401.doi:10.1109/APS.2015.7305089.

[4] T. Tajima, H. J. Song, and M. Yaita, “Design and Analysis of LTCC-Integrated Planar Microstrip-to-Waveguide Transition at 300 GHz,” IEEE Transactions on Microwave Theory and Techniques, vol. 64, no.1, pp. 106-114, 2015.doi: 10.1109/TMTT.2015.2504474.

[5] M. Giese, J. Waldhelm, and A.F. Jacob, “A wideband differential microstrip-to-waveguide transition at W-band,” German Microwave Conference, 2015, pp.174-177.doi: 10.1109/GEMIC.2015.7107781.

[6] M. GIESE, T. Meinhardt, and A. F. Jacob, “Compact wideband single-ended and differential microstrip-to-waveguide transitions at W-band,” IEEE MTT-S International Microwave Symposium (IMS),2015, pp. 1-4.doi: 10.1109/MWSYM.2015.7167143.

[7] E. Topak, J. Hasch, and T. Zwick, “Compact Topside Millimeter-Wave Waveguide-to-Microstrip Transitions,” IEEE Microwave and Wireless Components Letters, vol. 23, no. 12, pp. 641-643, 2013. doi: 10.1109/LMWC.2013.2284824.

[8] S.V. Mottonen, “Wideband Coplanar Waveguide-to-Rectangular Waveguide Transition Using Fin-Line Taper,” IEEE Microwave and Wireless Components Letters, vol. 20, no. 15, pp. 119-121, 2005.doi:10.1109/LMWC.2004.842855.

[9] Y. Zhang, J. Ruiz-cruz, KZaki, and A. J. Piolto, “A waveguide to microstrip inline transition with very simple modular assembly,” IEEE Microwave and Wireless Components Letters, vol. 20, no. 9, pp. 480–482, 2010.Doi:10.1109/LMWC.2010.2056358.

[10] Y. C. Leong and S. Weinreb, “Full Band Waveguide-to-Microstrip Probe Transitions,” IEEE MTT-S International Microwave Symposium Digest, Anaheim, 1999, pp. 1435-1438.doi:10.1109/MWSYM.1999.780219.

[11] Y. Tilhov, J.W. Moon, Y.J. Kim,et al, “Refined Characterization Of E-Plane Waveguide To Microstrip Transition For Millimeter-Wave Applications,” IEEE Microwave Conference, 2000, pp.1187-1190. doi: 10.1109/APMC.2000.926043.

[12] K. Y. Han and C. K. Pao, “A V-band Waveguide to Microstrip Inline Transition,” IEEE MTT-S International Microwave Symposium Digest, Montreal, 2012, pp. 1-3. doi: 10.1109/MWSYM.2012.6259752.

[13] Ke Li, Minghua Zhao, and Yong Fan, “A W Band Low-Loss Waveguide-To-Microstrip Probe Transition For Millimeter-Wave Applications,” Microwave and Millimeter Wave Circuits and System Technology (MMWCST), 2012, pp.1-3.doi: 10.1109/MMWCST.2012.6238136.

[14] T. Ho and Y.C. Shih, “Spectral-Domain Analysis of E-plane Waveguide to Microstrip Transitions,” IEEE Trans. Microwave Theory and Techniques, vol. 37, no. 2,388-392, 1989.doi:10.1109/22.20065

[15] H. B. Lee and T. Itoh, “A Systematic Optimum Design of Waveguide-to-Microstrip Transition,” IEEE Trans. Microwave Theory and Techniques, vol. 45, no. 5, pp. 803-809, 1997. doi:10.1109/22.575603.

[16] S. Liorente-romanoand B. Dorta-naranjo, “Design, Implementation and Measurements of Ka-band Waveguide-to-microstrip Transitions,” IEEE Microwave Conference,2002, pp.1-4. Doi10.1109/EUMA.2002.339378

[17] Xiaoxing Ma and Ruimin Xu, “A Broadband W-band E-plan Waveguide-to-Microstrip Probe Transition,” Microwave Conference, 2008, pp.1-4. doi: 10.1109/APMC.2008.4958471.

[18] David M. Poza r, Microwave Engineering, New York: John Wiley & Sons,1998, pp. 246-249.

Reply to the Report of Reviewer

We thank the Reviewer for his comments which we have found very useful in improvement of the manuscript. Based on these comments, we have made careful modification on the original manuscript. All changes make to the file are in red color and underlined. The Reviewer’s comments are point-by-point responded as below:

There is still one issue to be corrected. The transition was only tested in a back-to-back configuration with a fixed-length line in between. This is not a rigorous proof that your transition is well matched to the microstrip line. If the microstrip-line length is an integer multiple of half wavelengths, its characteristic impedance does not matter. A more rigorous experiment would include two different back-to-back configurations with two different-length microstrips. The difference in length as close to lambda/4 as possible. Are you able to do that? Maybe you already have similar data from measurements? This would give a much higher value to the whole article.

We just have similar data from measurements, so we added the sentence of “For rigorous verification of the well matched transition, we did further experiences. The experiments include two back-to-back configurations with two different-length microstrips. The lengths of microstrips in two back-to-back configurations are $\lambda/4 + \mathrm{L}_{\mathrm{fix}}$ and $\lambda/2 + \mathrm{L}_{\mathrm{fix}}$, respectively. The waveguide-to-microstrip transition with different length of microstrips are fabricated and assembled in a similar waveguide cavity. Figure 11 shows the measured results of the back to back transition structure with three different length of microstrip line ($\mathrm{L}_{\mathrm{fix}}$, $\lambda/4 + \mathrm{L}_{\mathrm{fix}}$, $\lambda/2 + \mathrm{L}_{\mathrm{fix}}$).The measured of insertion loss is less than 2 dB from 75GHz to 105GHz in all different length. The additional insertion loss of the measured data can be also attributed to the problems caused by the fabrication and assembly errors. The return loss is better than 11dB over the frequency range from 75 GHz to 105GHz, and is not about the length of microstrip line. These results certify that the proposed transition is well matched to the microstrip line.” (line 5 of page 8, in revised manuscript).

We added Figure11 of Measured results of the back to back transition structure with different length of microstrip line to proof that the transition is well matched to the microstrip line. (line 1 of page 9, in revised manuscript)

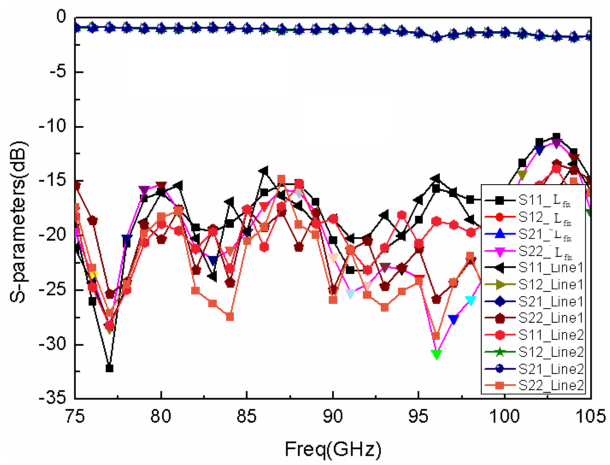

Figure 12. Measured results of the back to back transition structure with different length of microstrip line